ELSEVIER
www.elsevier.com/locate/pnucene
Available online at www.sciencedirect.com
SCIENCE DIRECT®
doi:10.1016/j.pnucene.2005.05.027
Progress in Nuclear Energy, Vol. 47, No. 1-4, pp. 283-291, 2005

0149-1970/$ - see front matter

REACTOR TECHNOLOGY DEVELOPMENT UNDER THE HTTR PROJECT

TAKAKAZU TAKIZUKA

Oarai Research Establishment, Japan Atomic Energy Research Institute,
Niihori 3607, Narita-cho, Oarai-machi, Ibaraki-ken, 311-1394 Japan

ABSTRACT

JAERI is developing HTR technology, hydrogen production technology, and system integration technology under the HTTR Project. The HTTR is the Japanese first HTR with a 30-MW thermal power. The first criticality of the HTTR was achieved in 1998, and the full-power operation at an outlet coolant temperature of 850°C was attained in 2001. The outlet coolant temperature was reached to 950°C in 2004. A seven-year program on the gas turbine HTR was launched in 2001. The program consists of the design of a GTHTR300 plant and R&D on a closed-cycle helium gas turbine system for the GTHTR300. It is designed to have a 600-MW thermal power at an outlet coolant temperature of 850°C and a 275-MW electric power. The objectives of the program are to establish a feasible plant design and to demonstrate key technologies for the helium gas turbine. The GTHTR300 design will demonstrate competitive economy and high degree of safety. It will also provide technology basis of VHTRs for power generation, hydrogen production, and cogeneration.

KEYWORDS

HTR; HTTR; GTHTR300; Gas turbine; Cogeneration

1. INTRODUCTION

High Temperature Reactors (HTRs) have a unique capability of producing high temperature heat of about 1000°C that enables high efficiencies in power generation and opens up possibilities to other process heat applications. A regenerative gas turbine is ideally suited as a high-efficiency power conversion system for an HTR power plant. Among process heat applications, hydrogen production through thermo-chemical processes has recently received special attention in the hope of massive production of clean fuel from water.

JAERI has carried out research and development on the HTR and high temperature heat utilization since 1969. The HTTR (High Temperature Engineering Test Reactor) is a 30-MWt HTR that was designed and constructed by JAERI, and is now under operation. The construction of the HTTR was initiated at the Oarai Research Establishment of JAERI in 1991. The HTTR attained the first criticality on November 10, 1998.

The JAERI's HTTR project is aiming at developing the HTR technology, hydrogen production technology and system integration technology to couple a chemical process with the HTR. The HTR technology development includes the HTTR operation and testing, gas turbine HTR plant design, R&D on helium gas turbines, and design study of a cogeneration HTR plant. This paper describes the present status of the HTR technology development under the HTTR project.

The present study has been carried out under the contact of research between JAERI and the Ministry of Education, Sports, Culture, Science and Technology of Japan (MEXT).

2. HTTR

The HTTR (Shiozawa, 2004) is a graphite-moderated, helium gas-cooled reactor that is designed to produce 30-MW thermal power at 850°C outlet coolant temperature in the rated operation and 950°C at the high-temperature test operation. Construction of the HTTR was initiated in March 1991. The HTTR achieved the first criticality in November 1998. As a test reactor, the HTTR has various purposes; establishment of HTR technology, demonstration of HTR safety operation and inherent safety characteristics, demonstration of nuclear heat utilization, irradiation of HTR fuel and materials in an HTR condition, and provision for testing equipment for basic research.

Table 1 lists the main specifications of the HTTR. The reactor is constructed of a reactor pressure vessel, fuel elements, replaceable and permanent reflector blocks, core support structures, control rods, etc., as shown in **Fig. 1**. The reactor pressure vessel is 13.2 m in height and 5.5 m in diameter. It contains an active core with a height of 2.9 m and a diameter of 2.3 m. The core average power density is 2.5 MW/m^3. Thirty fuel columns and seven control columns are arrayed in the active core. The fuel column consists of hexagonal-shaped fuel elements of 360 mm across the flats and 580 mm high. The fuel element is a pin-in-block type, consisting of a graphite block and fuel rods. The primary helium coolant at 395°C enters the core from the upper plenum, flows downward through the core, and exits to the hot plenum at 850-950°C. The total coolant flow rate is 10.2 kg/s for 950°C operation, and the effective core coolant flow is 88%.

The cooling system of the HTTR consists of a main cooling system, an auxiliary cooling system and a vessel cooling system, as shown in **Fig. 2**. The main cooling system consists of a primary cooling system, a secondary helium cooling system, and a pressurized water cooling system. The primary cooling system is composed of a helium/helium intermediate heat exchanger, a primary pressurized water cooler, four primary gas circulators, a primary concentric hot gas duct, etc. The intermediate heat exchanger is a vertical helical-coil counter-flow type heat exchanger that transfers high-temperature heat to the secondary helium system. Heat transfer tubes of the intermediate heat exchanger are made of Hastelloy-XR. The design pressure difference between the primary and secondary sides is 0.1 MPa. The secondary helium cooling system is composed of a secondary pressurized water cooler, a secondary gas circulator, a secondary concentric hot gas duct, etc.

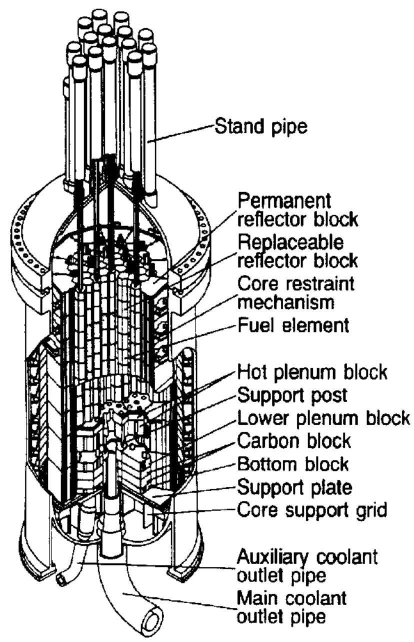

Fig. 1. Cutaway view of the RPV and core of the HTTR

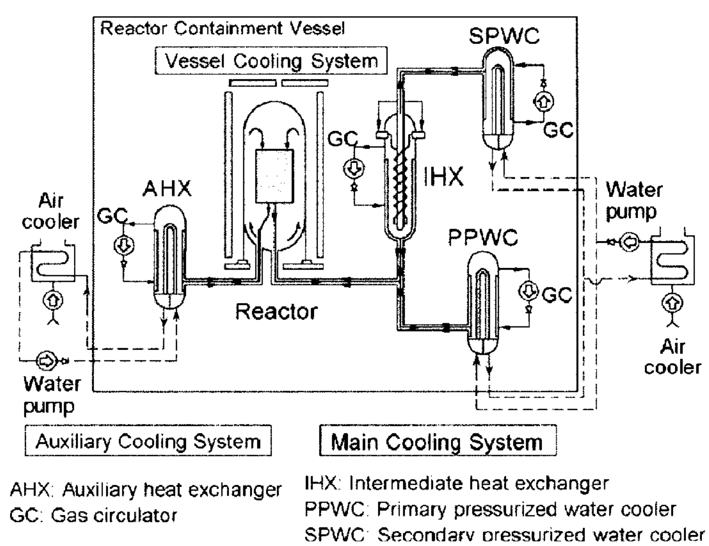

Fig. 2. Cooling system of the HTTR

The HTTR has two modes of loop operation, single loaded mode and parallel loaded mode, regarding the loading of heat exchangers for both of the rated operation and the high temperature test operation. In the single loaded operation, the secondary cooling system is not operated and the primary pressurized water cooler alone removes 30-MW heat whereas in the parallel loaded operation the secondary cooling is operated and the intermediate heat exchanger and the primary pressurized water cooler remove 10-MW and 20-MW heat, respectively. The objectives of the parallel loaded operation are to test the intermediate heat exchanger and the secondary cooling system, and eventually to provide high-temperature heat to a hydrogen production test facility to be connected to the HTTR.

Table 1. Major specifications of HTTR

Thermal power	30 MW
Outlet coolant temperature	850/950°C
Inlet coolant temperature	395°C
Fuel loading	Off-load, 1 batch
Core diameter × height	2.3 m × 2.9 m
Average core power density	2.5 MW/ m^3
Coolant flow rate	10.2 kg/s (950°C operation)
Primary coolant pressure	4.0 MPa

The HTTR attained the full-power operation at the rated outlet coolant temperature of 850°C in December 2001. The outlet coolant temperature of 950°C was achieved in April 2004 (Fujikawa, 2004).

3. GTHTR300 PLANT DESIGN

The GTHTR300 is a JAERI proposed design concept of a gas-turbine high-temperature reactor plant with 600-MW thermal power at 850°C outlet coolant temperature. Based on experience gained with HTTR, JAERI initiated a design and R&D for the GTHTR300 power plant in 2001. The objective of the project is to establish a feasible plant design and helium gas-turbine technology with ultimate goals for demonstration of a prototype in 2010s and for commercialization in 2020s in Japan.

The GTHTR300 design (Kunitomi, 2002; Takada, 2002) features modular plant, fully inherent and passive reactor safety, improved pin-in-block type fuel element, high burnup and long refuelling interval, conventional steel reactor pressure vessel, non-intercooled Brayton cycle, horizontal single-shaft turbo-machine, magnetic bearings to support turbo-machine rotor, and separate containment of turbo-machine and heat exchangers.

The entire primary system of the GTHTR300 is housed in three steel pressure vessels; reactor pressure vessel, power conversion vessel, and heat exchanger vessel, interconnected through coaxial double piping, as shown in **Fig. 3**. The reactor pressure vessel contains an annular reactor core. The vessel is cooled by a bypass flow of low temperature helium gas from the compressor outlet. The power conversion vessel contains a horizontal, single-shaft turbo-machine consisting of a turbo-compressor and an electric generator. Horizontal turbo-machine layout is to minimize the demands on load capacity of axial magnetic bearings and auxiliary bearings. A recuperator and a pre-cooler, together with primary control valves are contained in the heat exchanger vessel. Helium gas at 6.88 MPa is heated through the reactor core from 587°C up to 850°C, and then introduced into the turbine inlet to drive the turbine. The gas-turbine cycle of the GTHTR300 design generates 274.6 MW electric power for 600-MW reactor thermal power at 45.7% thermal efficiency. The major design parameters of the GTHTR300 are summarized in **Table 2**.

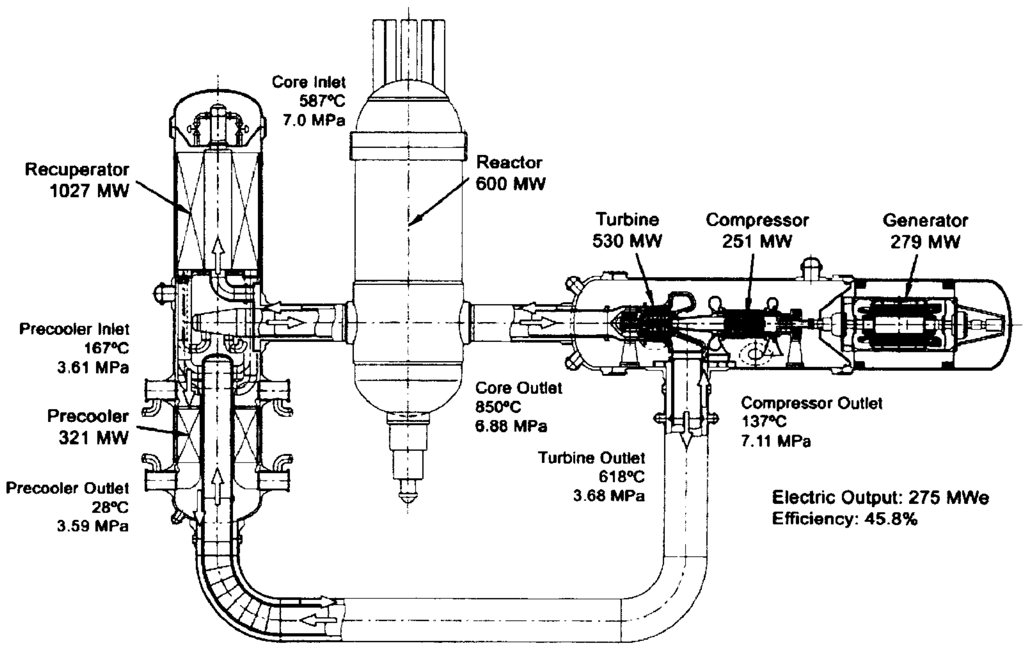

Fig. 3. System layout of the GTHTR300

Table 2. Major design parameters of the GTHTR300

Thermal power	600 MW
Electric power	274.6 MW
Outlet/Inlet coolant temperature	850°C/588.6°C
Fuel loading	Off-load, 2 batch
Core diameter × height	3.6/5.5 m × 8 m
Average core power density	5.8 MW/m^3
Coolant flow rate	449.7 kg/s
Primary coolant pressure	3.52-7.11 MPa

4. HELIUM GAS TURBINE TECHNOLOGY

The gas-turbine cycle of the GTHTR300 is designed to generate 274.6 MW electric power for 600-MW reactor thermal power at 45.7% thermal efficiency.

The compressor is a 20-stage axial-flow compressor with a pressure ratio of 2.0. The design aims at a high efficiency around 90%. At the design point, a polytropic efficiency of 90.5% and a surge margin of 30% are predicted for the GTHTR300 compressor. The turbine is a 6-stage axial-flow turbine with a pressure ratio of 1.87. The turbine design aims at a high efficiency and a low turbine bypass flow. The turbine has non-cooling blades made of Nickel-base super alloy. At the design point, polytropic efficiency of 92.8% and the turbine bypass flow rate of 1% are predicted for the GTHTR300 turbine.

The rotor system of the GTHTR 300 turbo-machine consists of a turbo-compressor rotor, a generator rotor, a flexible diaphragm coupling, four radial magnetic bearings, and an axial magnetic bearing. The rated rotational speed of the rotor system is 3600 rpm. Rotor dynamics analyses were made for the rotor system to detail the rotor design and to determine the specifications of the magnetic bearings. For magnetic bearings with a low stiffness around 1.0×10^9 N/m, the turbo-compressor rotor has two critical speeds of rigid mode and one critical speed of bending mode below the rated speed, and the generator rotor has two critical speeds of rigid mode and two critical speeds of bending mode.

The objectives of the R&D program are to verify the design and to demonstrate key technologies of the power conversion system. The R&D program consists of three subscale model tests; compressor aerodynamics performance test, magnetic bearing development test, and gas-turbine system operation and control test (Takizuka, 2004).

The compressor aerodynamic performance test is aiming at verifying the aerodynamic performance and design method of the helium compressor. A 1/3-scale, 4-stage compressor test model and a helium gas loop were designed and fabricated. The compressor test model is shown in **Fig. 4**. The first testing was successfully completed in March 2003 and demonstrated a high efficiency at around 88% and a sufficient surge margin of around 33%. The second testing is scheduled in the end of 2004.

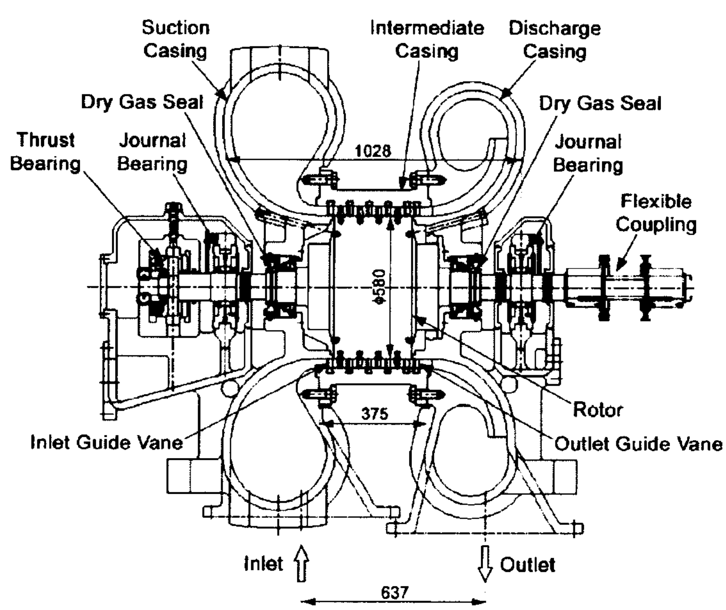

Fig. 4. One-third scale, four-stage compressor test model

The magnetic bearing development test is aiming at developing the technology of the magnetic bearing supported rotor system. The test rig is composed of 1/3-scale turbo-compressor and generator rotor models that are connected together by a flexible diaphragm coupling. Design of the rotor models and magnetic bearings were completed and fabrication of the rotor model was started. Testing of magnetic bearing performance, unbalance response, stability, and auxiliary bearing reliability will be carried out together with development of advanced control method in the program.

The gas-turbine system operation and control test is aiming at demonstrate operability and controllability of the closed-cycle gas-turbine system. Preliminary design was made for the test facility that is an integrated scaled model of the GTHTR300 power conversion system. Pressurized helium gas at around 1 MPa is used as the working fluid, and an electric heater simulates the reactor. Planned test modes are normal operation, start-up, shutdown, load change, loss of load, and emergency shutdown.

5. COGENERATION PLANT DESIGN

A preliminary design study is underway to establish a concept of a cogeneration plant GTHTR300C that produce both electricity and hydrogen based on the GTHTR300 design. The design aims at providing high-temperature heat at around 950°C to a hydrogen production plant. R&D on nuclear hydrogen production based on thermo-chemical IS process is underway at JAERI (Onuki, 2005). International collaboration on the very high-temperature gas-cooled reactor (VHTR) and the hydrogen production is under discussion in the Generation IV International Forum.

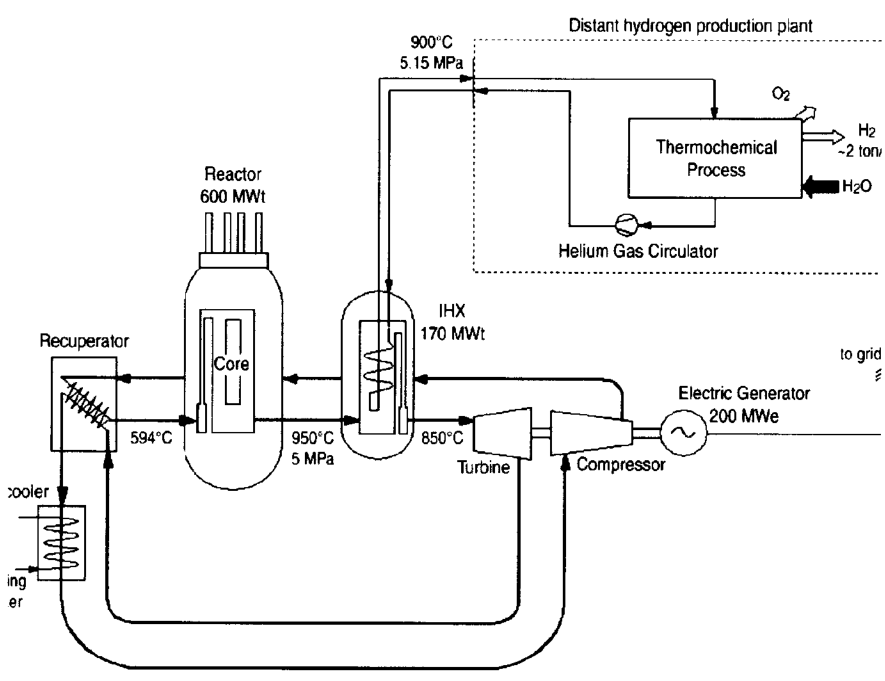

Fig. 5. GTHTR300C power and hydrogen cogeneration cycle scheme

Figure 5 shows the system layout of the GTHTR300C (Kunitomi, 2004). The helically coiled intermediate heat exchanger is installed between the reactor pressure vessel and the power conversion vessel. No major design change of the primary components was made except the addition of the intermediate heat exchanger. Major design parameters of the GTHTR300C are listed in **Table 3**.

Table 3. Major design parameters of the GTHTR300C

Thermal power	600 MW
Electric power	202 MW
Outlet/Inlet coolant temperature	950°C/594°C
Fuel loading	Off-load, 2 batch
Core diameter × height	3.6/5.5 m × 8 m
Average core power density	5.8 MW/m^3
Coolant flow rate	324 kg/s
Primary coolant pressure	2.55-5.1 MPa

The reactor thermal power is 600 MWt, the same as that of GTHTR300. The outlet coolant gas temperature is raised from 850°C to 950°C, and the primary coolant pressure is lowered from about 7 MPa to about 5 MPa. Of the total reactor thermal power, about 170 MWt is used for the process heat through the intermediate heat exchanger and the balance for the gas turbine system. The reactor outlet helium gas of 950°C enters the shell side of the intermediate heat exchanger and exits it at 850°C. The helium gas at 850°C drives the turbine and approximately 200 MWe of electricity is generated.

6. CONCLUDING REMARKS

JAERI is carrying out the HTR technology development under the HTTR project. The HTTR successfully achieved full power at the outlet coolant temperature of 950°C. Design of the GTHTR300 power plant and R&D on a gas-turbine system are underway with a goal of near-term commercial deployment. The GTHTR300 design will demonstrate competitive economy and high degree of safety, and the R&D on helium gas turbines will establish technology of high-efficiency power conversion.

REFERENCES

Fujikawa, S., Hayashi, H., Nakazawa, T., Kawasaki, K., Iyoku, T., Nakagawa, S., Sakaba, N. (2004), Achievement of Reactor-Outlet Coolant Temperature of 950°C in HTTR, J. Nucl. Sci. Technol. 41(12).

Kunitomi, K., Katanishi, S., Takada, S., Takizuka, T., Nakata, T., Yan, X., Takei, M., Kosugiyama, S., Shiozawa, S. (2002), Design Study on Gas Turbine High Temperature Reactor (GTHTR300), Trans. At. Energy Soc. Japan 1 (4), 352-360.

Kunitomi, K. and Yan, X. (2004), GTHTR300C for Hydrogen Cogeneration, 12th Int. Conf. on Nucl. Eng., Virginia, 25-29 April.

Onuki, K., Inagaki, Y., Hino, R., Tachibana, Y. (2005), R&D on Nuclear Hydrogen Production Using HTGR at JAERI, this issue.

Shiozawa, S., Fujikawa, S., Iyoku, T., Kunitomi, K., Tachibana, Y. (2004), Overview of HTTR Design Features, Nucl. Eng. Des., 233, 11-21.

Takada, S., Takizuka, T., Kunitomi, K., Yan, X., Katanishi, S., Kosugiyama, S., Minatsuki, I., Miyoshi, Y. (2002), Design Study of Power Conversion system for the Gas Turbine High Temperature Reactor (GTHTR300), Trans. At. Energy Soc. Japan, 1 (4), 341-351.

Takizuka, T., Takada, S., Yan, X., Kosugiyama, S., Katanishi, S., Kunitomi, K. (2004), R&D on Power Conversion System for Gas Turbine High Temperature Reactors", Nucl. Eng. Des., 233, 329-346.